

CHAPTER 9

Land Application: Agricultural Crop Responses

INTRODUCTION

The value of sewage sludge and biosolids has been recognized for decades. In 1863, Justice von Liebig in *The Natural Laws of Husbandry* stated:

Even the most ignorant peasant is quite aware that the rain falling upon his dung heap washes away a great many silver dollars and that it would be much more profitable to him to have on his fields what now poisons the air of this house and the streets of the villages; but he looks on unconcerned and leaves matters to take their course, because they have always gone in the same way.

With the advent of sewage treatment in the 1880s, some limited land application occurred. When the activated sludge process was initiated, the use of sludge as organic fertilizer material became of interest (Noer, 1925). Sewage crop irrigation was practiced as early as 1872 in Augusta, Maine (Jewell and Seabrook, 1979).

Extensive research on crop responses to land application of biosolids began in the early 1970s. Much of this research took place in conjunction with an evaluation of heavy metal uptake. This early research included greenhouse studies and field plots. It soon became apparent that greenhouse or pot studies provided very limited information on crop yields, primarily because of the root growth restrictions. However, greenhouse studies did provide trends and directions for field studies. In the greenhouse, the studies could explore many more variations, trials and evaluations. This permitted the researcher to narrow the focus in field experiments.

Considerable research was conducted by the University of Illinois in conjunction with The Metropolitan Sanitary District of Chicago, University of Minnesota, United States Department of Agriculture, Agricultural Research Service, University of California and others. Much research was also conducted by experiment stations under regional auspices, e.g., the regional project W-124 titled: Optimum Utilization of Sewage Sludge on Cropland.

This research was the basis for United States Environmental Protection Agency's (USEPA) early regulations 40 CFR 257, published in 1979 and titled: Criteria for Classification of Solid Waste Disposal Facilities and Practices: Final Interim Final and Proposed Regulations (*Fed. Reg.* 44(179): 53460-53468).

Some of these early publications included:

- *Proceedings Joint Conference Recycling Municipal Sludges and Effluents on Land*, Champaign, Illinois, July 9–13, 1973, National Association of State Universities and Land-Grant Colleges, Washington, D.C.
- *Soils for Management of Organic Wastes and Wastewaters*, 1977, Elliott, L.F. and F.J. Stevenson (Eds.), American Society of Agronomy, Crop Science Society of America and Soil Science Society of America, Madison, WI.
- *Utilizing Municipal Sewage Wastewaters and Sludges on Land for Agricultural Production*, 1977, North Central Regional Extension publication No. 52.
- *Recycling Treated Municipal Wastewater and Sludge through Forest and Cropland*, 1973, Sopper, W.E. and L.T. Kardos (Eds.), Pennsylvania State University Press, University Park.

Page and Chang (1994) provided insight on the growth of technical papers during the period 1971 to 1993. They reported that a casual search of the computer database AGRICOLA showed 876 references from 1970 to March 1993. The greatest number of publications appeared in the 1980s. In 1986 alone, nearly 100 technical papers were published. In 1999, a search of the database Biological Abstracts that cites technical publications worldwide revealed more than 2400 references.

Over the years, numerous changes have occurred that influenced the results observed. Analytical methods have improved, allowing for more accurate results. Improvements in wastewater technology and industrial pretreatment have had probably the greatest influence on biosolids management on crop growth and uptake of trace elements. Major changes have occurred in biosolids' characteristics. Discharges from industrial inputs have been dramatically reduced and domestic plumbing systems shifted from lead and copper to plastic. These factors reduced the input of certain undesirable trace elements. Changes in dewatering systems have also affected the chemical characteristics of biosolids. Vacuum filters using ferric chloride and lime gave way to belt filter presses and centrifuges using polymers.

Several federal laws have also influenced biosolids management. These include:

- The Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500)
- The Resource Conservation and Recovery Act of 1976 (Public Law 94-580)
- The Marine Protection, Research and Sanctuaries Act of 1972 (Public Law 92-532).

These laws provided grants for the construction of municipal wastewater treatment plants, including sludge processing and management facilities. Public Law 92-500 provided for the pretreatment of toxic industrial wastes prior to discharge into a municipal sewer system, and prohibited the discharge of sewage sludge into navigable waters without a permit from USEPA. Public Law 92-532 restricted and

eventually prohibited ocean dumping of sewage sludge. Thus, major metropolitan areas such as New York, Philadelphia, Los Angeles and communities in New Jersey had to seek alternatives such as incineration, land application, composting and heat drying.

The objective of this chapter is to provide data on the effects of land application of biosolids to crops. These effects could be the result of added nutrients and minor plant elements, addition of water under droughty conditions, or improved soil physical properties. Only data on crop productivity are presented. This chapter is divided into sections outlining early research data up until 1970 and later research data, from 1970 to the present.

In the years subsequent to 1970, the quality of biosolids has changed radically. These changes affected plant growth. The dewatering system switched to the use of different chemicals. In the 1970s and early 1980s, ferric chloride and lime were used in dewatering. With the advent of belt filter presses and centrifuges, polymers were used. Industrial pretreatment also resulted in lower heavy metal inputs, lessening the potential for phytotoxicity at high application rates. The application of biosolids containing high levels of phytotoxic heavy metals can result in decreased crop yields (Berti and Jacobs, 1996). Although considerable research has been published outside North America, the data presented here focus on North American studies.

Because much effort was spent on the pros and cons of sludge and biosolids application with respect to heavy metal uptake, many researchers lost sight of the economic value of biosolids application. In many cases if not most, researchers reported only on the chemical constituents of the crops and not on yields. For farmers, the economic benefits of biosolids application are most important, providing the crop is valuable from a health perspective.

AGRONOMIC CROPS

Research Results Prior to 1970

Although for centuries human waste has been applied to soils as a fertilizer for crops, very little has been documented about the benefit of biosolids in agriculture. Bartow and Hatfield (1915) reported that when 1 ton per acre of activated sludge was used, the yield of lettuce increased by 50% and radishes by 300%, compared to check plots. In field trials, Richard and Sawyer (1922) compared the value of activated sludge to that of barnyard manure and ammonium sulfate and reported that the yields of grass, barley and potatoes were similar to the other nitrogen sources. Brown (1921, 1922) also reported that activated sludge was a good source of nitrogen. Noer (1925, 1926) conducted field trials with cabbage, tomatoes, corn and potatoes and found that activated sludge was a satisfactory source of nitrogen.

Lunt (1953) evaluated the potential use of digested biosolids in Connecticut. He found that plant response differed for different soils and that for several plants, liming was needed to obtain a favorable response. He indicated that germination of plants could be inhibited if planting was made directly into soil amended with fresh

sewage sludge. Anderson (1959) reported that the use of dried activated sludge as a fertilizer increased from 13,500 to 84,684 metric tons in 1957. During that period, farmers made more modest use of dried digested biosolids and sludge in mixed fertilizers.

In 1967 the University of Illinois initiated a major research effort, sponsored by the Metropolitan Sanitary District of Greater Chicago (Hinesly and Sosewitz, 1969). Initial field studies were conducted on corn and soybean.

Research Results 1970 to 2001

During the early 1970s, the University of Illinois studies applied liquid digested biosolids to several different soils (Lynam et al., 1975). Yields were statistically significantly higher (1% level) than the control in 1970 and 1973, even with lower rates of application. In other years, although there were differences because of the variation in the data, the results were not statistically significant. From 1968 to 1993, the average yield for corn grain in the control was 6.28 metric tons/ha, compared with 8.24 metric tons/ha in field tests with the optimum biosolids application rate.

Milne and Graveland (1972) reported that in a greenhouse using barley, significant increases (1% level) were obtained for barley grown on three soils, even at the rate of 101 metric tons/ha of biosolids. No toxicity was produced even at this high rate. Kelling et al. (1973) applied liquid digested biosolids to the soil surface and obtained increased yields of rye, maize and sorghum Sudan grass. However, they found that spreading biosolids on established alfalfa markedly reduced crown survival and lowered yields. Other glasshouse studies showed that yields of crops were depressed as Cu, Zn and Cr concentrations increased, but Ni had no appreciable effect. It appeared that Cr reduced the effects of the other metals (Cunningham et al., 1975).

Sabey and Hart (1975) also found that severe inhibition of germination of sorghum Sudan grass and millet resulted when seeded shortly after biosolids was incorporated into the soil. They did not find the same inhibition with wheat seeded three months after biosolids application. Giordano et al. (1975) reported that biosolids reduced the yield of mature bush bean pods due to excessive zinc. Forage yields of sweet corn in 1972 and 1973 were higher with biosolids.

One of the most extensive studies, initiated in 1971, was conducted by the USDA-Agricultural Research Service and the University of Minnesota (Linden et al., 1995). When biosolids applications were based on available N and crop-N demands, yields often were higher on biosolid-amended soil than those on areas receiving recommended additions of commercial fertilizer (Dowdy et al., 1976). Dowdy and Larson (1975) reported potato yields of 67.2 metric tons/ha (30 tons/acre) on plots that received 450 metric tons/ha (200 tons/acre) of anaerobically digested biosolids. Yields of 45 metric tons/ha (20 tons/acre) were considered good using commercial fertilizers under the same cultural conditions. They also reported a threefold increase in snap bean yields when biosolids, rather than commercial fertilizers, were used as the source of plant nutrients (see [Table 9.1](#)) on coarse sandy loam.

In California, Hyde (1976) reported that anaerobically digested biosolids applied to corn in a field study produced a significantly higher yield than a fertilized control.

Table 9.1 Edible Snap Bean Yields in 1974 as a Function of Biosolids Application

Treatment	Yield - mt/ha
Control	1.2
Fertilized — 675 kg/ha of 8-16-16 & 67 kg/ha N sidedress	5.4
<i>Biosolids application - May 1972</i>	
112 mt/ha	6.2
225 mt/ha	7.9
450 mt/ha	9.3
<i>Biosolids application — May 1972, October 1972 and September 1973 — three equal applications</i>	
337 mt/ha	9.0
675 mt/ha	12.9
1350 mt/ha	16.3

Source: Dowdy and Larson, 1975, *J. Environ. Qual.* 4: 278–282. With permission.

Kelling et al. (1973) applied liquid digested biosolids at rates of 3.75 to 60 metric tons dry solids to rye forage and Sudan-sorghum to two different soils. Yields tended to increase up to 7.5 Mg/ha on the silt loam soil and 15 Mg/ha on the sandy loam soil with dry solids biosolids application. Some crop yield reductions occurred at the 30 and 60 Mg/ha biosolids rates.

Yields of sorghum x Sudan grass hybrid sown directly after biosolids' application increased from 1.93–2.33 tonnes dry matter (DM) applied to soils with no biosolids, to 4.98–5.71 tonnes with 7.5–30 tonnes of biosolids and declined 4.27–4.33 tonnes with 60 tonnes of biosolids. Clapp et al. (1977) reported that corn yield means for three seasons were 13.8 Mg/ha fodder and 6.4 Mg/ha grain on the fertilizer control area and 14.5 Mg/ha fodder and 6.8 Mg/ha grain on the biosolid-treated area. Reed canarygrass dry matter yields for one cropping season were 7.8 Mg/ha on the fertilized area and 9.7 Mg/ha on the biosolids-treated area.

Considerable research conducted in the 1980s emphasized heavy metal uptake. Watson et al. (1985) reported on cotton yields. As they indicated, both the seed and lint are commercially valuable, but the lint is considered the most valuable. The medium rate of biosolids application (39 Mg/ha) appeared to give the best results during a 3-year study. Essentially, there were no significant differences in seed or lint yield when compared with the fertilized control.

USDA and the University of Minnesota conducted extensive research on the use of biosolids for crop production. Clapp et al. (1986) discovered yield advantages for several crops (see data in [Table 9.2](#)). Bidwell and Dowdy (1987), on the other hand, did not find a significant effect on corn stover yields. Corn grain yield from the control was significantly greater than from all the biosolids plots. Heckman et al. (1987) reported that dry matter production of nodulating soybeans was enhanced by application of biosolids, with the greatest increases occurring under moisture stress. However, with biosolids high in heavy metals, it appeared that nodulating dry matter decreased. Crop yield is perhaps the most important determinant of the economic value of biosolids as a substitute for commercial fertilizer (Linden et al., 1995). Corn has value as either a forage crop or a grain crop. Linden et al. (1995) evaluated the effect of biosolids on corn fodder and grain yields over 20 years (see

Table 9.2 Dry Matter Yields of Several Crops from Soil Treated with Biosolids, Compared with Fertilized Controls in Field Experiments

Crop	Biosolid Application		Yield			References
	Rate (Mg/ha/ Year)	Number of Years	Control (Mg/ha/ Year)	Biosolids (Mg/ha/Year)	Increase (%)	
Corn fodder ¹	116	4	14.9	20.5	38	Clapp et al., 1975
Grain			6.5	9.8	51	
Corn fodder ²	15	7	16.8	17.4	4	Clapp et al., 1983
Grain			7.9	8.6	9	
Reed canarygrass ²	18	7	9.8	11.2	14	Clapp et al., 1983
Corn fodder ³	116	5	17.6	19	8	Clapp et al., 1980
Grain			9.2	9.6	4	
Potato	450	1	1.8 ⁴	6.7	272	Dowdy et al., 1975
Snap bean	450	3	5.2	16.4	215	Dowdy et al., 1978

¹ Means of 3 years.

² Means of 7 years.

³ Means of 5 years, no additional biosolids.

⁴ Unfertilized.

Source: Adapted from Clapp et al., 1986.

Figure 9.1). During that period, the biosolids treatment produced significantly greater fodder yields. Corn grain yields were greater in 15 of the 20 years where biosolids were applied. Over the 20 years, the average corn grain yields were 8.6 Mg/ha (151 bushels per acre) in the biosolids treatments in comparison to 8.1 Mg/ha (140 bushels/acre) in the fertilized control treatments. The average corn fodder yields were 15.8 Mg/ha for the control fertilizer vs. 16.4 Mg/ha for the biosolids treatments.

Berti and Jacobs (1996) evaluated the chemistry and phytotoxicity of soil trace elements as a result of repeated biosolids application. They measured the yield of corn grain, soybean grain and sorghum Sudan grass. The harvest data are shown in Table 9.3. Historically, the use of biosolids has resulted in yields often higher than where recommended applications of fertilizer have been used. In many areas of the United States, farmers continue to use biosolids for their nutrient benefits and increased yields.

FORESTRY AND RECLAMATION

Forestry and reclamation are two excellent uses for biosolids, especially Class B. The major advantages are:

- Use of biosolids in nonfood chain crops
- Revegetation of mined soils
- Reducing runoff and erosion from disturbed soils
- Prevention of surface and groundwater from disturbed soils
- Increased productivity of timber

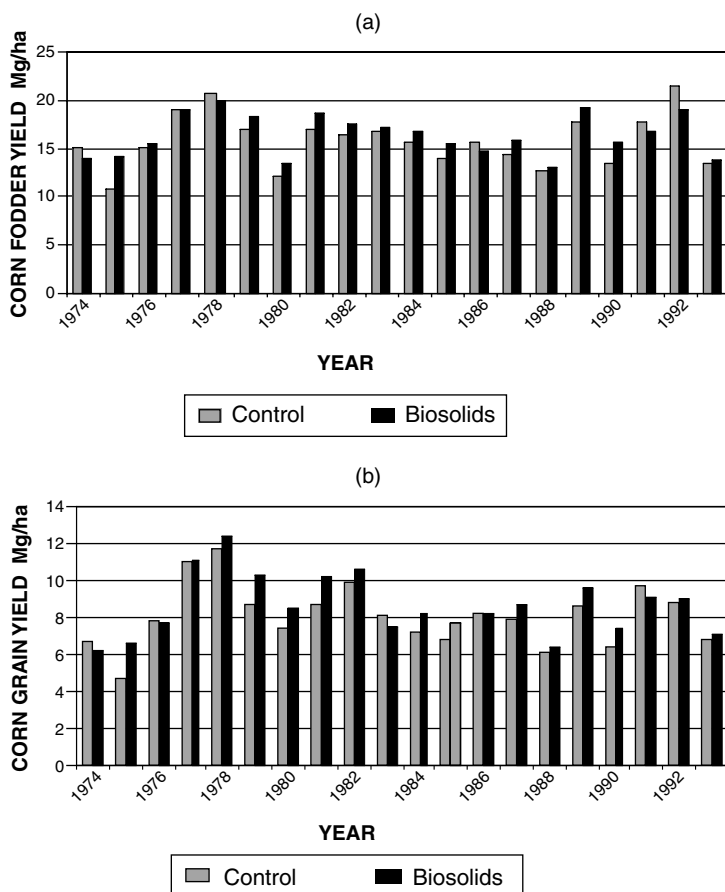


Figure 9.1 Comparison between a fertilizer control and biosolids on corn fodder (a) and grain (b) yield. (After Clapp et al., 1994.)

Table 9.3 Yields of Corn Grain, Soybean Grain and Sorghum-Sudan Grass

Crop	Control	Biosolids Rate – Mg/ha		
		240	870	690
Corn grain ¹	6.1 ± 2.8b ²	7.6 ± 3.1a	6.1 ± 2.2b	7.7 ± 3.1a
Soybean grain ³	2.3 ± 1.0a	2.2 ± 1.2a	No plants	2.0 ± 1.1b
Sorghum-Sudan grass ⁴	9.1 ± 2.2b	11.0 ± 2.5a	8.4 ± 2.4b	11.4 ± 3.1a

¹ Average of 1985 to 1990 harvests, at 15.5% moisture. Corn was not grown in 1989.

² Values in rows followed by the same letter are not significantly different at the P = 0.05 level.

³ Average of 1985 to 1989 harvests, at 13% moisture.

⁴ Average 1985 to 1988 dry weight basis.

Source: Berti and Jacobs, 1996, *J. Environ. Qual.* 25: 1025–1032. With permission.

Forestry

Considerable research has been carried out on the application of biosolids to forestland. Much of the research was done at the University of Washington. Early studies concentrated on forest seedling treated with sewage sludge, biosolids, or biosolids compost (Gouin, 1977; Gouin et al., 1978; Bledsoe and Zasoski, 1981). Zasoski et al., (1983) reported that in a nursery-bed, Douglas fir, Sitka spruce, black cottonwood and Lombardy poplar all grew well in biosolids-amended media. Western hemlock and western red cedar, however, did not do well in biosolids-amended media. Lambert and Weidensaul (1982) reported the use of sludge and biosolids on tree seedlings and Christmas tree production. Growth of several species was better than the control at low rates. At the rate of 180 Mg/ha, transplant survival was significantly reduced.

The University of Washington initiated studies in 1975 to evaluate the effects of biosolids application to forestland. Cole (1982) provided a brief history of the University of Washington's research on the application of biosolids to forestland. One study (Holmes et al., 1993) over three periods, 1985–1987, 1987–1989 and 1989–1991 showed the following:

- Basal area and volume growth increments of the biosolids and thinned treatment outgrew the control and the non-biosolids thinned treatments.
- Quadratic mean diameter growth was largest in the biosolids treatment.
- Applying biosolids appears to have enhanced stand growth.

Several studies were conducted on the use of biosolids for poplar production since poplars produce biomass at higher rates than most north-temperate woody species (Cullington et al., 1997). Zabek (1995) showed that hybrid poplars responded well to biosolids.

Reclamation

One of the best potential uses of biosolids is in reclaiming disturbed lands. Sopper (1993) reported that most of the disturbed lands are from mining of coal, sand, gravel, stone, clay, copper, iron ore, phosphate rock and other minerals. He indicated that 1.6 million ha have been disturbed by surface mining and thousands of acres will be mined annually. Many of these disturbed areas release heavy metals and other contaminants to surface and groundwaters. They are unsightly and are poor habitats to much wildlife.

Using biosolids for mine reclamation offers several major advantages:

- Provides macro- and micronutrients for vegetation establishment
- Improves the soil physical properties, resulting in less erosion and runoff
- Improves the soil biological properties
- Increases land productivity
- Provides food for wildlife

Table 9.4 Reclamation of Disturbed Land

Type of Disturbed Land	State	Biosolids Type	References
Acid strip mine spoil/refuse	PA	Digested dewatered/ composted/liquid	McCormick and Borden, 1973 Kardos et al., 1979 Hill et al., 1979 Murray et al., 1981 Sopper and Kerr, 1982 Sopper et al., 1981 Sopper and Seaker, 1982; 1984 Seaker and Sopper, 1983; 1984; 1987 Dressler et al., 1986 Alberici et al., 1989
Zinc smelter site	PA	Digested dewatered	Sopper, 1989 Sopper and McMahon, 1988
Coal mine spoil	CO	Digested dewatered	Topper and Sabey, 1986 Voos and Sabey, 1987
Copper mine spoil			Sabey et al., 1990
Copper mine	TN	Digested dewatered	Berry, 1982
Strip mine spoils	IL	Digested liquid	Boesch, 1974 Lejcher and Kunkle, 1974 Stucky and Newman, 1977 Hinesley and Redborg, 1984 Stucky et al., 1980 Roth et al., 1982 Joost et al., 1987 Pietz et al., 1989
Strip mine spoil	KY	Digested dewatered	Feuerbacher et al., 1980
	OH	Digested dewatered	Haghiri and Sutton, 1982
	MD	Digested, composted	Griebel et al., 1979
Gravel spoils	MD	Composted	Hornick et al., 1982
C and D canal dredge material	DE	Digested dewatered	Palazzo and Reynolds, 1991
Lignite overburden	TX	Digested dewatered	Cocke and Brown, 1987
Strip mine spoil	VA	Composted	Scanlon et al., 1973
	WV	Digested; digested dewatered, composted	Mathias et al., 1979 Tunison et al., 1982
Iron ore tailings	WI	Digested dewatered	Morrison and Hardell, 1982
Taconite tailings	WI	Digested dewatered	Cavey and Bowles, 1982

Sopper (1993) summarized the research results in land reclamation for the past 20 years. He cited more than 80 publications on the subject. Sopper concluded that the use of municipal sewage biosolids in reclamation and revegetation of drastically disturbed land has been extensively studied. The results to 1993 were encouraging and showed that biosolids, properly applied, can be used to revegetate mined lands in an environmentally safe manner with no major adverse effect on the vegetation, soil, or groundwater. This practice does not pose any significant threat to animal or human health.

This section will not attempt to cover this field since Sopper has done an excellent comprehensive review. [Table 9.4](#) provides several of the citations indicated by Sopper

Table 9.5 Average Dry Matter Production of Several Grasses and Legumes after Three Growing Seasons on Biosolids-Amended Mine Spoil Land

Species	Biosolids Application Rate (Mg/ha)			
	0	40	75	150
	(kg/ha)			
Reed canarygrass	1701	6519	6408	9120
Orchard grass	922	3115	4578	6157
Tall fescue	825	3760	5077	7664
Penngift crownvetch	1937	3283	3326	5070
Bird's-foot trefoil	1586	2712	3731	5518

Sources: Sopper, 1990; 1993.

(1993). Carrello (1990) also provided a 10-year summary on the use of sludge/biosolids on coal mine spoils.

Sopper (1993) reported that the productivity and fertility of disturbed lands had been substantially improved in most cases by biosolids' application. In West Virginia, where biosolids were applied to mine spoil at rates of 112 and 224 Mg/ha, yield of tall fescue surpassed controls by more than 818% (Mathias et al., 1979).

Sopper (1990) investigated the growth of numerous grasses and legumes on biosolids-amended burned anthracite coal refuse bank. Coverage ranged from 0% to 97%. Excellent coverage was with reed canarygrass, orchard grass and tall fescue, at rates exceeding 40 Mg/ha. Penngift crownvetch averaged more than 68% on plots receiving more than 40 Mg/ha. The average dry matter production for several species is shown in [Table 9.5](#).

CONCLUSION

Scientists have conducted extensive research on the use of biosolids for agricultural crops, horticulture, forestry and reclamation. Biosolids provide macro- and micronutrients. Under certain conditions, the addition of water is also beneficial. The organic matter in biosolids or biosolids products can improve soil physical properties such as soil structure, bulk density, soil moisture, compaction and aeration. These improvements provide for better root growth and development. Plants are better able to utilize plant nutrients and water. In many cases, the use of biosolids increased yield and quality of plants.

Most biosolids are land applied as USEPA Class B materials. These biosolids have restrictions on the type of cropping system where they can be used. Forestry, reclamation and nonfood chain crops (cotton, hay, etc.) are excellent uses for biosolids.

Class A biosolids, such as compost and heat-dried products, are permitted for use on all crops. However, since the additional treatment to produce a Class A is more costly and these products have excellent handling qualities, they are often used in horticulture where crop values are high.

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